APPENDIX D

DETAILED GALVANIC CATHODIC PROTECTION DESIGN EXAMPLE BASED ON PIKE ISLAND AUXILIARY LOCK GATES USING SLAB ANODES

D-1. Design for Lock Gates

Figure D-1 shows a Pike Island auxiliary miter gate. This gate is approximately 18.85 m (62 ft) long and 10.64 m (35 ft) high. With the river at normal water level, portions of each gate will always be submerged, and other portions may be submerged or exposed as lockages occur. During times of high water, more gate surfaces will be submerged, and, under conditions of flood, the entire gates may be submerged. The usual water depth is 9.12 m (30 ft).

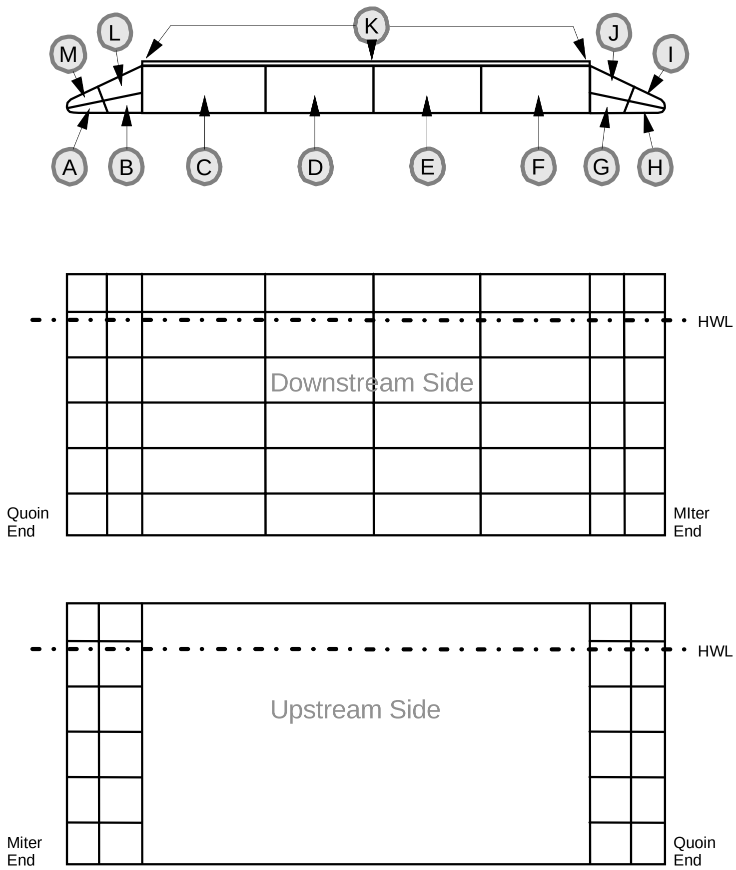

FIGURE D-1. LOCK GATE VERTICAL, DOWNSTREAM AND UPSTREAM STRUCTURAL LAYOUT

The gates are constructed of welded structural steel, horizontally framed, with a cast pintle. The downstream side of the gate consists of a pattern of rectangular chambers closed on five faces and open to the water on the sixth face. The upstream face of the gate consists of a large skin plate (area K on sketch) over the major portion of the face and two columns of small chambers (chambers M, L, J & I) at the quoin and miter ends of the gate.

The main (large) chambers (chambers C, D, E, and F) on the downstream face of the gate are set in four columns and are approximately 3.66 m (12 ft) wide, varying in height from 1.01 m (3 ft 4 in.) to 1.82 m (6 ft), with a depth of 1.06 m (3 ft 6 in.). The two sets of vertically aligned chambers, at the quoin and miter ends of the gates (chambers A, B, G, & H), are much smaller and irregularly shaped. There are six horizontally aligned rows of chambers placed one above the other in each vertical column, giving a total of 48 chambers on the downstream side, however, only the five lower chambers are normally submerged.

D-2. <u>Design Data</u>

The following information, with values and assumptions included here for the current example, must be known in order to design any CPS for a Lock Gate Structure:

a. The lock is located in fresh water with a resistivity of 1900 ohm-centimeters. Note: This information must be measured either on-site or from sample of water obtained on-site. Either should be obtained when water is at it's highest resistivity (usually in fall when rainfall is least and run-off is least).

b. Water velocity is less than 1524 mm/s (5 ft/s).

c. Water contains debris, and icing will occur in the winter.

d. The gate surfaces have a new vinyl paint coating, minimum of 0.15 mm (6 mils) thick, with not more than 1 percent of the area bare because of holidays in the coating.

e. The coating will deteriorate during 20 years of exposure. Based on the recent experience with the coating systems being applied to modern structures, it is reasonable and conservative to assume that 15 percent of the area will become bare in 20 years.

f. Design for 75.35 mA/m^2 (7.0 mA/ft^2) (moving fresh water).

g. Design for a 20-year life.

h. Design for normally submerged surface areas.

i. For galvanic anode systems, the anodes required must be based on the maximum (final) current requirement over the anode design life since the system has no adjustment capability.

D-3. Computations

a. Find the Surface Area to be Protected

(1) Upstream Side

i. *Area of skin plate K*: While the gate has an overall height of 10.64 m, it is normally submerged to a depth of 9.14 feet. The width of the gate covered by the skin plate is measured to be 14.50 m. Therefore, the submerged surface area of the skin plate = 14.50 m x 9.14 m = 132.53 m^2 (1,427 ft^2).

ii. *Larger chamber areas J & L adjacent to skin plate*: 5 each larger normally submerged chambers adjacent to skin plate each having 6.50 m^2 (70 ft^2) surface area. Note: the sixth chamber at top of each column of chambers is normally above the high-water line and will not be provided with protection.

iii. *Smaller chambers I & M adjacent to quoin and miter end:* five each smaller, normally submerged chambers adjacent to skin plate each having 3.7 m^2 (40 ft^2) surface area. Note: the sixth chamber at top of each column of chambers is normally above the high water line and will not be provided with protection.

(2) Downstream Side

i. *Large chambers C, D, E, & F*: With five normally submerged chamber stacked in four columns, there are a total of 20 chambers. Note that the sixth chamber at top of each column of chambers is normally above the high-water line and will not be provided with protection. While their height varies slightly, the design will be based on the large chamber with greatest height (which has the largest surface area). The dimensions for the largest of these chambers is 3.66 m (12 ft) wide, 1.82 m (6 ft) high 1.06 m (3.5 ft) deep. Based on this information, the individual submerged area of chambers C, D, E, and F = area of both ends of the chambers + area of top and both of each chamber + area of back of chamber = (2 x 1.06 x 1.82) + (2 x 1.06 x 3.66) + (1.82 x 3.66) = 3.85 + 7.76 + 6.66 = 18.87 m^2 (203.2 ft^2).

ii. *Small chambers A, B, G & H*: With five normally submerged chambers stacked in four columns, there are a total of 20 chambers. Again, note that the sixth chamber at top of each column of chambers is normally above the high-water line and will not be provided with protection. The smallest chambers (A and H) have the same width of 0.9 meters each with an average depth of 0.2 meters while the two larger chambers (B and G) have a width of 1.1 meters each and an average depth of 0.4 meters. Each chamber will be designed on the chamber having the greatest height of 1.82 m. Thus the area of the smallest chambers A and H = (2 x 0.2 x 1.82) + (2 x 0.2 x 0.9) + (1.82 x 0.9) = 0.78+ 0.36 + 1.64 = 2.78 m^2 (30 ft^2). The area of the next smallest chambers B & G = (2 x 0.4 x 1.82) + (2 x 0.4 x 1.1) + (1.82 x 1.1) = 1.46+ 0.88 + 2.0 = 4.34 m^2 (46.7 ft^2).

(3) <u>Create a Summary Table of Area for Each Chamber (Table D-1)</u>

TABLE D-1. CHAMBER AREA VALUES

Chamber or Surface ID	**Side of Gate**	**Type of Area**	**No. Sub-merged**	**Area Each m^2 (ft^2)**	**Area Total m^2 (ft^2)**
A & H	Downstream	Chamber	5 x 2 = 10	2.78 (30)	27.8 (300)
B & G	Downstream	Chamber	5 x 2 = 10	4.34 (46.7)	43.4 (467)
C, D, E, & F	Downstream	Chamber	5 x 2 = 10	18.9 (203)	189 (2030)
I & M	Upstream	Chamber	5 x 2 = 10	3.7 (40)	37 (400)
J & L	Upstream	Chamber	5 x 2 = 10	6.50 (70)	65.0 (700)
K	Upstream	Skin Plate	1	133 (1,427)	133 (1,427)
Total Submerged Area					495.2 (5,324)

b. <u>Calculate the Current Required for a Single Structure Component</u>

$$I = A \times I'(1.0 - C_E) \qquad \text{[EQ 1]}$$

where:

A = surface area to be protected

I' = required current density per bare ft^2 of steel submerged to adequately protect gate = 75.35 mA/m^2 = 7 mA/ft^2

C_E = coating efficiency (0.85 at end of 20 years service)

Example calculation only for skin plate requirement: I = 133 m^2 x 75.35 mA/m^2 x (1 – 0.85) = 1503 mA

c. Create a Table of Current Requirements for Each Structure Component (Table D-2)

TABLE D-2. CURRENT REQUIREMENTS FOR EACH STRUCTURE COMPONENT

Chamber or Surface ID	Side of Gate	Type of Area	Area Each m^2	Current Density I' (mA/m^2)	1 - C_E	Min. No. Anodes*	Current Required per Unit (mA)	Current Required for All Units (mA)
A & H	Downstream	Chamber	2.78	75.35	.15	1	31.4	314.2
B & G	Downstream	Chamber	4.34	75.35	.15	1	49.1	490.5
C, D, E, F	Downstream	Chamber	18.9	75.35	.15	2	213.6	2136.0
I & M	Upstream	Chamber	3.7	75.35	.15	1	41.8	418.2
J & L	Upstream	Chamber	6.50	75.35	.15	1	73.5	734.7
K	Upstream	Skin Plate	133	75.35	.15	14	1503.2	1503.2
Total Current Required								5596.8

* To ensure uniform current distribution, it is normally good design practice to provide at least 1 galvanic anode per 10 m^2 structure surface to be protected.

d. Select Anode Alloy

Refer to Table C-3 in Appendix C. Because the water resistivity is approximately 1900 ohm-cm, it is apparent that the preferred anode alloy material, considering both the current output available and anode life, is H-1 magnesium alloy (Grade A or B). If none of the available shapes provide sufficient current, re-evaluate using high-potential magnesium alloy anodes. If anode life proves too short with both magnesium alloys, then high-purity zinc alloy anodes should be considered.

e. Select Anode Size

Size is governed by the amount of current required for each size chamber and the skin plate. Because there are multiple chamber sizes to consider, start with the smallest surface and then sequentially evaluate the larger chambers. Designing the smaller components is simpler and will familiarize the designer with the process.

(1) Chambers A and H

i. Current Required per unit = 31.4 mA

ii. Initial Anode Selection: Refer to Tables C-4 through C-10 in Appendix C. Select the table with the resistivity closest to that of the measured water resistivity. In this case, the water resistivity is 1900 ohm-cm, so the appropriate reference would be Table C-6, Appendix C, for 2000 ohm-cm resistivity water. The bar chart included in Table C-6 provides a visual aid to help quickly determine which anodes may be appropriate for this chamber. Based on Table C-6, the

1x6x12SBE, 2x8x8SBE, 2x9x18SCE, and 4x9x18SCE anode sizes appear to be the most appropriate.

iii. Anode Selection Based On Life: The desired anode life is 20 years. Using Figure C-2, Appendix C, only the 2x9x18 or 4x9x18 shapes have sufficient metal weight to meet the 20-year service life requirement at the 31.4 mA output desired. Because the 2x9x18SCE has sufficient life and will provide the desired current for this chamber, install one 2x9x18SCE plastisol-coated H-1 Alloy Grade A or B magnesium alloy anode for the 10 A and H Chambers. Also check and note that one anode per chamber is sufficient for good current distribution in these chambers (see Table D-2).

(2) Chambers B and G

i. Current Required per unit = 49.1 mA

ii. Initial Anode Selection: Again refer to Tables C-4 through C-10 in Appendix C. Select the table with the resistivity closest to that of the measured water resistivity. As before, the water resistivity is 1900 ohm-cm, so the appropriate reference is Table C-6, Appendix C. Again, based on the data and bar chart visual aid, the only anodes to be considered are the 2x9x18SBE and the 4x9x18SBE.

iii. Anode Selection Based On Life: The desired anode life is 20 years. Using Figure C-2, Appendix C, only the 2x9x18 or 4x9x18 shapes have sufficient metal weight to meet the 20-year life requirement at the 49.1 mA output desired. Again, because the 2x9x18SBE has sufficient life and will provide the desired current for this chamber, install one 2x9x18SBE, H-1 Alloy, Grade A or B magnesium alloy anode with bare sides and face for the 10 B and G Chambers. Also check and note that one anode per chamber is sufficient for good current distribution in these chambers (see Table D-2).

(3) Chambers C, D, E, and F

i. Current Required per unit = 213.6 mA

ii. Initial Anode Selection: Again refer to Tables C-4 through C-10 in Appendix C. Select the table with the resistivity closest to that of the measured water resistivity. As before, the water resistivity is 1900 ohm-cm, so the appropriate reference is Table C-6, Appendix C. Based on the information gained from the designs for the previous smaller chambers, no single anode will be able to meet the current requirement for these large chambers. Instead, it would be preferable to use the least number of H-1 alloy magnesium anodes that will provide the desired current of 213.6 mA. Table C-6 shows that the 4x8x18SBE H-1 alloy magnesium anodes provides the highest current output of 64 mA. Four anodes of this model will provide 256 mA, which is sufficient to meet the design requirement. Also note that the 2x9x18SBE H-1 alloy magnesium anode provides a current output of 53 mA. Four anodes of this model will provide 212 mA, which is extremely close to the design current requirement. Both anodes may be considered, however, because the water resistivity is slightly lower than the 2000 ohm-cm value used in Table C-6. Therefore, both anodes (with four per chamber) would in fact meet the desired current requirement.

iii. Anode Selection Based On Life: As before, the desired anode service life is 20 years. Figure C-2 shows that only the 2x9x18 shape has sufficient magnesium metal weight to meet the 20-year service life requirement at the desired 53 mA/anode output. Thus, install four 2x9x18SBE, H-1, Grade A or B Alloy, magnesium anodes with bare sides and face for the 40 C, D, E, and F Chambers. It should be noted that the four anodes per chamber exceeds the minimum number of two anodes required for good current distribution (see Table D-2).

(4) Chambers I and M

i. Current Required per unit = 41.8 mA

ii. Initial Anode Selection: Again refer to Tables C-4 through C-10 in Appendix C. Select the table with the resistivity closest to that of the measured water resistivity. As before, the water resistivity is 1900 ohm-cm, so the appropriate reference is Table C-6, Appendix C. Based on the data and bar chart visual aid, the only anodes to be considered are the 2x9x18SBE and the 4x9x18SBE.

iii. Anode Selection Based On Life: The desired anode life is 20 years. Using Figure C-2, Appendix C, only the 2x9x18 or 4x9x18 shapes have sufficient metal weight to meet the 20-year life at the 41.8 mA output desired. Because the 2x9x18SBE has sufficient life and will provide the desired current for this chamber, install one 2x9x18SBE H-1 Alloy Grade A or B magnesium alloy anode with bare sides and face for the 10 I and M Chambers. Also check and note that one anode per chamber is sufficient for good current distribution in these chambers (see Table D-2).

(5) Chambers J and L

i. Current Required per unit = 73.5 mA

ii. Initial Anode Selection: Again refer to Tables C-4 through C-10 in Appendix C. Select the table with the resistivity closest to that of the measured water resistivity. As before, the water resistivity is 1900 ohm-cm, so the appropriate reference is Table C-6, Appendix C. Based on the data and bar chart visual aid, it can be seen that none of the H-1 alloy magnesium anodes will provide the desired current. However, high-potential alloy magnesium anodes in configuration 2x9x18SBE provide 72 mA, which is very close to the calculated current, while the 4x9x18SBE will provide more than enough at 87 mA.

iii. Anode Selection Based On Life: Again the desired service life is 20 years. Figure C-2, Appendix C, shows that only the 4x9x18 shape has sufficient metal weight to meet the 20-year service life requirement at the 73.5 mA output desired. Thus, install one 4x9x18SBE high-potential alloy magnesium anode with bare sides and face for the 10 J and L Chambers. Also check and note that one anode per chamber is sufficient for good current distribution in these chambers (see Table D-2).

(6) *Surface K (Skin Plate)*

i. Current Required = 1503.2 mA

ii. Initial Anode Selection:

(a) Again refer to Tables C-4 through C-10 in Appendix C. Select the table with the resistivity closest to that of the measured water resistivity. As before, the water resistivity is 1900 ohm-cm, so the appropriate reference is Table C-6, Appendix C. Based on the information gained from the designs for the previous smaller chambers, no single anode will be able to meet the current requirement for these large chambers. Instead, it would be preferable to use the least number of H-1 alloy magnesium anodes that will provide the desired current of 1503.2 mA. Table C-6 indicates that the 4x8x18SBE H-1 alloy magnesium anode provides the highest current output, 64 mA, while the 2x9x18SBE H-1 alloy magnesium anode provides current output of 53 mA. Note that the 2x9x18SCE high-potential alloy magnesium anode also will output 50 mA. Any one of these three anodes could be used, but the 4 in. thick H-1 alloy anode will cost almost twice as much as the 2 in. thick anode cast from the same alloy at the same width and length.

(b) An important consideration in anode selection for the Skin Plate is the value of Plastisol coating of the anode. Although the coating restricts current flow from the anode to the Skin Plate it in fact improves current distribution because the current from the sides of the anode cannot flow to the steel directly adjacent to the anode. With bare edge anodes it is necessary to place a neoprene rubber shield behind the anode to extend beyond the anode perimeter at least 2 in. This shield must be glued in place, typically with 100% silicon caulk. Unfortunately, this shielding material can be damaged by debris or ice floating down the river and impacting primarily on the exposed skin plate anodes. Consequently, for Skin Plate anodes only, if floating debris or ice are expected in the application, it is normally recommended that the entire anode be coated with Plastisol from which a window is cut to expose a limited operating surface. In the current example, for the skin plate galvanic anode system, use 30 2x9x18SCE high-potential Alloy plastisol-coated magnesium anodes. These will provide 1500 mA of current, which is extremely close to the design current requirement. Both anodes may be considered because the water resistivity is slightly lower than the values for chart's 2000 ohm-cm resistivity given in Table C-6, so 30 anodes will in fact meet the desired current requirement.

iii. Anode Selection Based On Life: The desired anode life is 20 years. Figure C-2 indicates that only the 2x9x18 shape has sufficient magnesium metal weight to meet the 20-year service life requirement at the 50 mA/anode output desired. Thus, install 30 2x9x18SCE high-potential Alloy, Plastisol-coated magnesium anodes with coated back and sides to protect the skin plate. It should be noted that the 30 anodes exceeds the minimum number of 1four anodes required for good current distribution (see Table D-2).

f. Develop Anode Locations for Each Structure Element

Placement of anodes is simply a geometric process of distributing the anodes uniformly on each protected structural element to achieve good current distribution.

(1) Chambers A, B, G, H, I, J, L, and M

In this example, locating of the anodes in the chamber requiring only one anode is simple in that the anode will be placed on the back surface of each chamber, centered both vertically and horizontally.

(2) Chambers C, D, E, and F

Where more than one anode is required in each chamber, the anodes will be centered vertically within the chamber, but they must be evenly distributed along the side and back panels of the chamber to achieve uniform current distribution. This is done by 'folding open' the three-sided box representing the anode into a flat rectangle, then mathematically distributing the anodes horizontally within that rectangle. The only chambers in this example requiring multiple anodes are the 20 large chambers whose depth is 1 meter and width is 3.7 meters. Because there are four anodes to be distributed around the vertical perimeter surface of the chamber, the overall perimeter dimension of 5.7 meters is first divided by the number of anodes, i.e, four in this case (5.7 m/4 = 1.43 m). This value is used for the center-to-center (c-c) spacing of the four anodes. Then divide the c-c value by 2 to arrive at the setback distance from the front edge of the chamber for the two outermost anodes (1.43 m/2 = 0.71 m). Because the height of the chambers varies from 1 m to 1.8 m, the vertical center point location of the anodes is shown as one-half of the chamber height. The locations for the anodes in the large chambers is shown in Figure D-1).

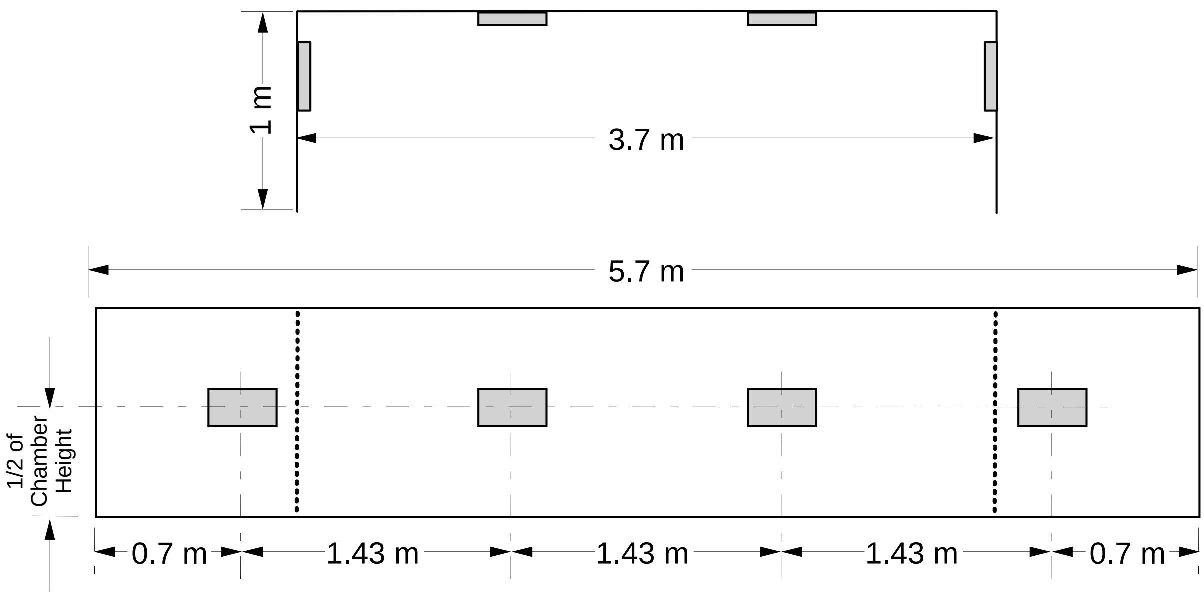

FIGURE D-1. GALVANIC SLAB ANODE LOCATIONS
IN LARGEST DOWNSTREAM GATE CHAMBERS

(3) Skin Plate

Because the Skin Plate will usually require multiple anodes distributed uniformly both vertically and horizontally, the design procedure is somewhat different than it is for the chamber anode configuration. In this case, use the total square footage of the submerged skin plate surface (133 m^2) and divide by the number of anodes required to protect the skin plate (30 anodes) = 133 m^2/30 anodes = 4.43 m^2/anode. The width and height dimensions of each square area to be protected by each anode is the square root of that area. To calculate the width and height of the area to be protected by each anode, use the following formula:

$$W_{A1} = H_{A1} = \sqrt{A_{A1}}$$

where:

W_{A1} = width of area protected by one anode

H_{A1} = height of area to be protected by one anode

A_{A1} = area to be protected by one anode

For this particular skin plate, the height and width of the area to be protected by each anode is calculated below:

$$W_{A1} = H_{A1} = \sqrt{4.43} = 2.1 meters$$

The number of anodes in each row across the skin plate is calculated by dividing the width of the skin plate by the width of the area to be protected by a single anode. In this design, the skin plate width is 14.50 meters and the single anode area width is 2.1 meters, or 14.50/2.1 = 6.9 anodes.

The number of anodes in each column across the skin plate is calculated by dividing the submerged height of the skin plate by the height of the rectangular area to be protected by a single anode. In this design, the skin plate submerged height is 9.12 meters and the single anode area height is 2.1 meters, or 9.12/2.1 = 4.32 anodes.

To complete the calculation, round up both values to the next whole number. In this example, 6.9 becomes seven anodes equally spaced across the skin plate, and 4.32 becomes five anodes spaced equally down from the normal high-water line to the bottom of the skin plate. As in the case of the large chamber anodes, the horizontal spacing of the anodes is determined simply by dividing the number of seven horizontally spaced anodes (in this case) into the skin plate width of 14.5 meters = 14.5/7 = 2.071 meters. The vertical spacing of the anodes is determined simply by dividing the number of five vertically spaced anodes (in this case) into the skin plate submerged height of 9.12 meters = 14.5/7 = 1.824 meters.

The layout for these anodes on the skin plate is shown in Figure D-2.

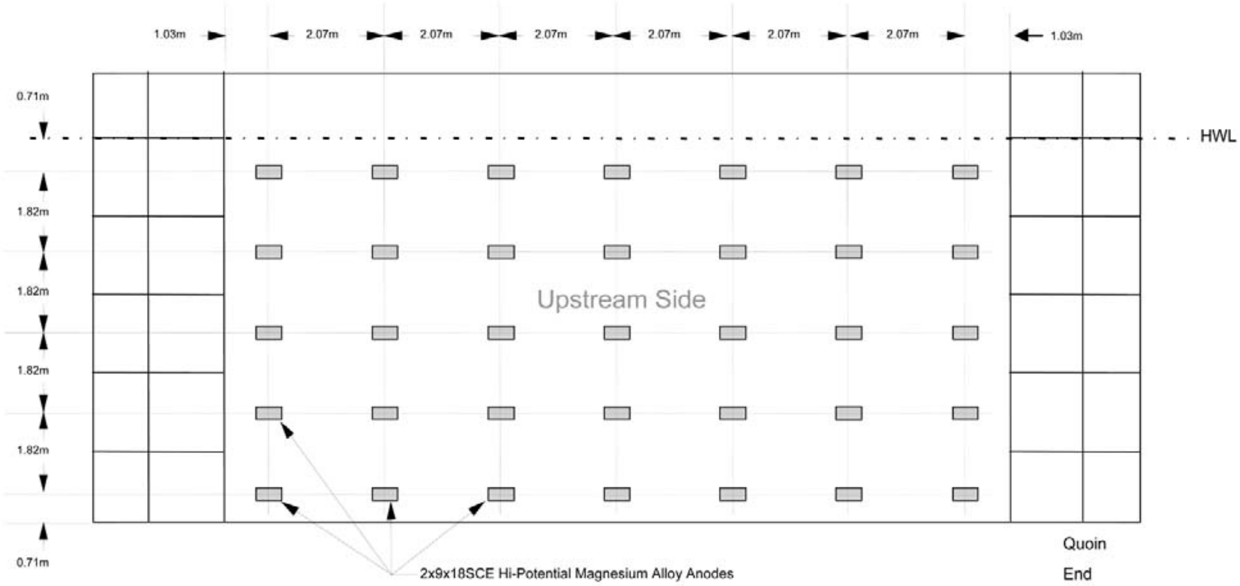

FIGURE D-2. EXAMPLE SLAB ANODE LAYOUT FOR UPSTREAM SIDE (SKIN PLATE)